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Large-scale interannual variability of climate

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Summary

Climate is discussed in terms of research into its interannual variability on large spatial scales. Some of the statistical properties of this variability are presented. Several examples of hemispheric-scale fluctuations are used to elucidate the physical mechanisms at work.

1. Introduction

Variability is an essential feature of climate. To regard the normal alone as an adequate expression of climate would be a serious error; it is better to regard current climate as the entire ensemble of recently observed atmospheric conditions. The possibility that the climate itself changes on time-scales of decades or longer will be discussed in other papers: the present paper is mainly concerned with atmospheric variations on time-scales of one to five years. Such variations may be regarded as expressions of the existing climate, rather than as changes of climate: there is, of course, no real dividing line between interannual fluctuations and climatic change.

Most of the research into large-scale interannual variability in the atmosphere has, until recently, been of an empirical nature, not only because of the need to establish the facts before setting up hypotheses and models, but also because of the difficulty in formulating relatively simple working hypotheses which not only fit the facts but also represent realistically the complex physics and dynamics of the atmosphere and ocean. A further limitation has been the impossibility of integrating complex numerical models through simulations of many years. This account will begin empirically by illustrating the magnitude of interannual variability, the statistical distributions to which it appears to conform, and the degree of regularity of the variability in time and space; but then an attempt will be made to examine the underlying causes of interannual variations, in the context of the tropical stratospheric quasi-biennial oscillation and of the large-scale tropical fluctuations known as the Southern Oscillation.

2. Illustrations of interannual variability

Variability of climate in terms of temperature and rainfall is a natural consequence of variability of the atmospheric circulation, which will therefore be the main subject of this section.

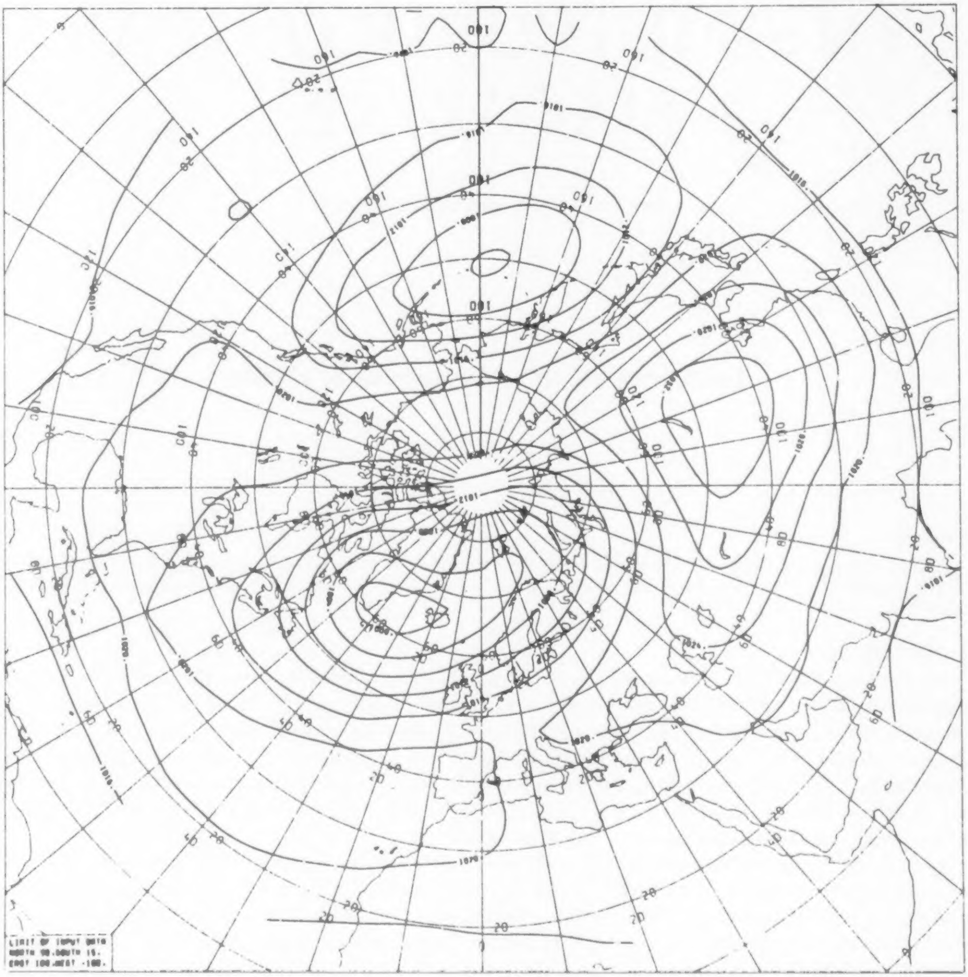

Figure 1(a). Normals of monthly mean pressure (mb) at mean sea level (MSL) for January. Data for 1900–80.

(a) *The magnitude of climatic variability*

The magnitude of the variability inherent in the atmospheric circulation is illustrated by Figs 1(a) and 1(b) which show the normal January mean-sea-level pressure pattern and the standard deviation of individual January averages. It is clear, from a comparison of the normal pressure gradients with the standard deviations, that the variability is sufficient occasionally to reverse major features, such as the mid-latitude westerlies in the Atlantic, for whole months. The maxima of variability are near the

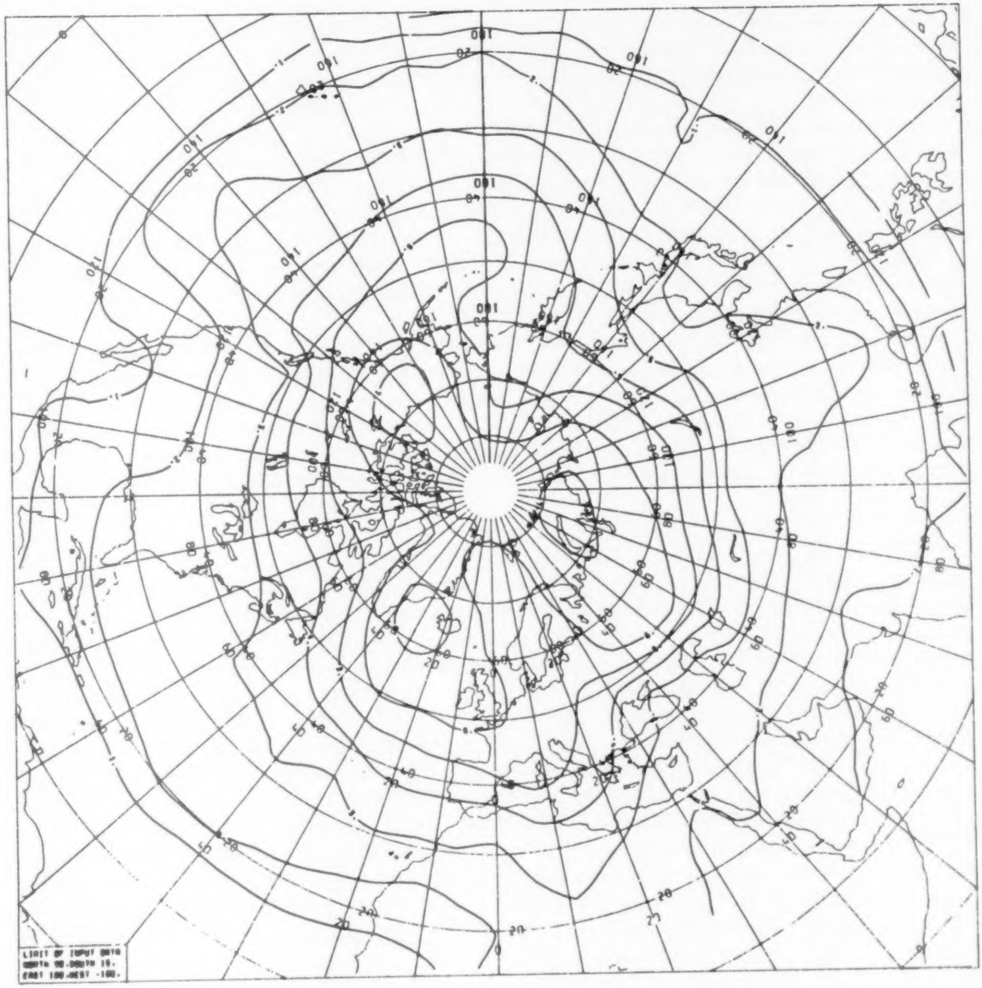

Figure 1(b). Standard deviations of monthly mean pressure at MSL (mb) for January. Data for 1900–80.

subpolar lows and have been found to be related not only to statistical scatter in the depths of individual depressions, but also to variability on time-scales of weeks, associated with the occurrence of major interruptions of the mid-latitude westerlies, i.e. blocking. The magnitude of the interannual variability of circulation is exemplified by the fact that the northern hemisphere atmospheric annual mean angular momentum varies by up to 25% (Rosen *et al.* 1976).

Circulation variability entails variability in cloud cover, resulting in variability in the earth's long-wave radiation budget as documented by Heddinghaus and Krueger (1981). The effects of circulation variability on local temperature and rainfall are a complex function of the earth's geography and will not be discussed here.

An important component of climatic variability is in the sea surface temperature. Figs 2(a) and 2(b) show the February normal of sea surface temperature and the standard deviation of individual February averages. In this case the variability is generally insufficient to reverse the north–south temperature gradient. However, the variability of sea surface temperature in some low-latitude regions, such as the tropical east Atlantic (Rowntree 1976) and the equatorial east Pacific (Bjerknes 1966, 1969), appears to be physically linked to the atmospheric variability, both locally and far afield. The equatorial east Pacific is discussed below in the context of the Southern Oscillation. The importance of the mid-latitude North Pacific has also been stressed (e.g. Namias 1978).

Attempts to simulate atmospheric variability with three-dimensional dynamical models have hitherto been thwarted by the computational difficulty and expense of including an ocean which interacts realistically with the atmosphere. However, in contrast to the above-mentioned results on sea surface temperature, Manabe and Hahn (1981) found that omission of interannual sea surface temperature variability from their general circulation model resulted in an underestimation of atmospheric variability only in the tropics, where the oceanic aspects of the Southern Oscillation could not be represented.

(b) *The statistical distribution of climate*

The possibility that uninterrupted westerly flow, and blocked flow, mentioned above, are two alternative equilibrium states for the mid-latitude atmosphere (cf. Charney and DeVore 1979), is suggested by the discovery that some measures of the circulation show skewness or even bimodality in their frequency distribution. The example in Fig. 3, Azores minus Iceland mean-sea-level pressure for winter months, is skew and slightly bimodal. The bimodality was found to be greater in periods when blocking was more frequent, e.g. 1940–81. The skewness is reflected in the statistical distribution of winter temperatures in central England, which are strongly controlled by the Atlantic flow. The Azores minus Iceland mean-sea-level pressure distribution for the other seasons is more nearly Gaussian.

The monthly averaging process applied to daily winter European temperatures also fails to produce a Gaussian frequency distribution of these temperatures because of the extreme coldness of easterly flows. By way of contrast, Parthasarathy and Mooley (1978) found that Indian summer monsoon rainfall conformed to a Gaussian distribution. Individual daily rainfall values are unlikely to approximate to a Gaussian distribution because a large frequency of dry days (zero rainfall) is likely to be superimposed on a J-shaped distribution for days with rain; but the daily Indian values must have satisfied the conditions in which the central-limit theorem applies, so that averaging produced a more Gaussian result.

(c) *Quasi-periodicity*

The best-known example of an almost periodic interannual variation is the quasi-biennial oscillation of wind direction and speed and temperature in the lower stratosphere in the tropics. The monthly mean 30 mb winds over Canton Island (Pacific) up to 1967, then over Gan (Indian Ocean), are shown in Fig. 4. It is possible to form such a composite series from two widely separated stations only because the quasi-biennial oscillation occurs on a global scale in the tropics with very little time-lag between different longitudes. The period of the oscillation is not constant; it varies from less than two years to about three years, and averages two years and three months. Periods near either two or three years tend to be favoured, and there are favoured seasons for changeover of the wind direction (Parker 1976). There is

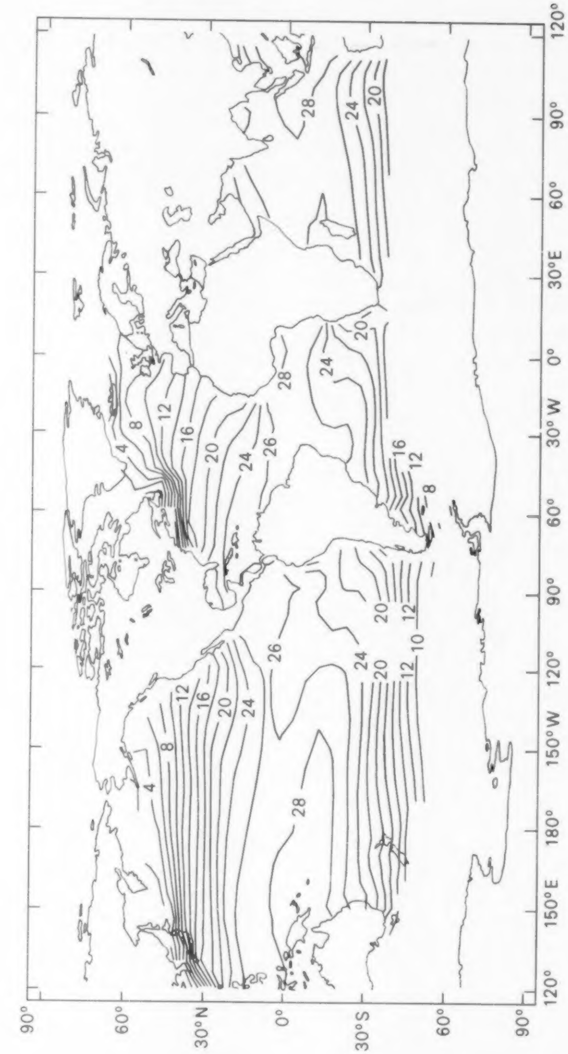

Figure 2(a). Normals of sea surface temperature (°C) for February. Data for: 1900–60, Atlantic area; 1931–60, other areas.

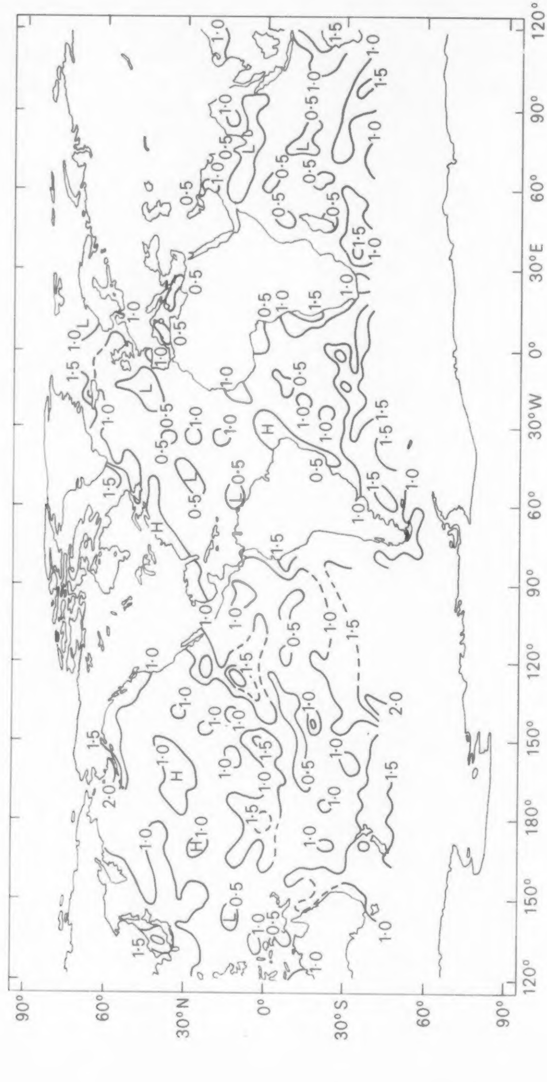

Figure 2(b). Standard deviations of sea surface temperature (°C) about monthly normals for February. Data for: 1900–60 Atlantic area, 1931–60 other areas.

also downwards phase propagation with, for example, changes in the 50 mb wind vector lagging by several months behind changes in the 30 mb wind vector.

The discovery of the tropical stratospheric quasi-biennial oscillation has been followed by very widespread reports of quasi-biennial behaviour in local tropospheric climate and circulation parameters. Parthasarathy and Mooley (1978) found a quasi-biennial oscillation in Indian monsoon rainfall, but this was not strong and regular enough to be used for annual forecasting. Ebdon (1975) documented differences in the mean northern hemisphere mid-latitude surface pressure and 500 mb geopotential patterns and in zonal winds aloft, according to the phase of the tropical quasi-biennial oscillation. Fig. 5 illustrates the mean-sea-level pressure anomalies for Julys with a westerly tropical quasi-biennial wind mode. The anticyclonic anomaly near the British Isles was found to be statistically significant at about the 5% level. In addition, not only Ebdon (1975) but also Angell and Korshover (1977) observed that the circumpolar upper-tropospheric vortex was smaller during the westerly phase of the tropical quasi-biennial oscillation, particularly in winter (Fig. 6), with an associated increase of tropospheric temperature of several tenths of a degree Celsius in mid-latitudes. Consequent effects on, for example, summer temperature and sunshine in the United Kingdom, were noted by Ebdon. Furthermore, Holton and Tan (1980) have demonstrated that there is a 50 mb and 1000 mb quasi-biennial oscillation in the geopotential and temperature of the northern polar regions. The two levels are

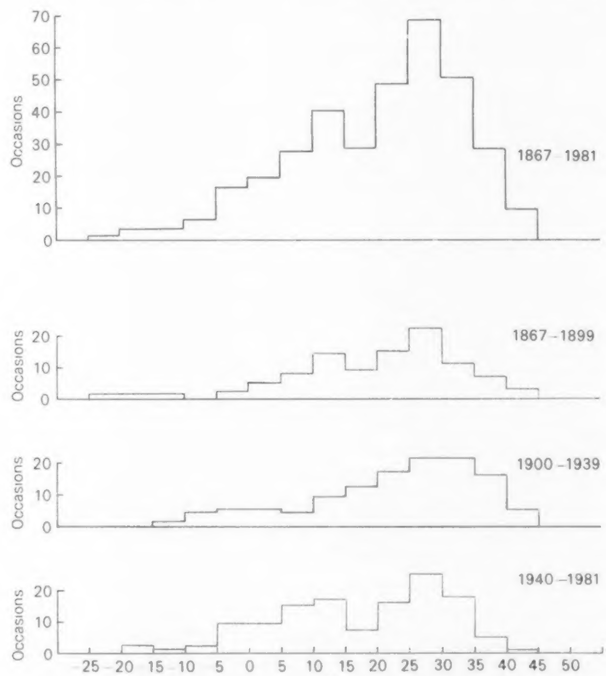

Figure 3. Ponta Delgada (Azores) minus Stykkisholmur (Iceland) mean-sea-level pressure (mb), winter months (up to December 1981).

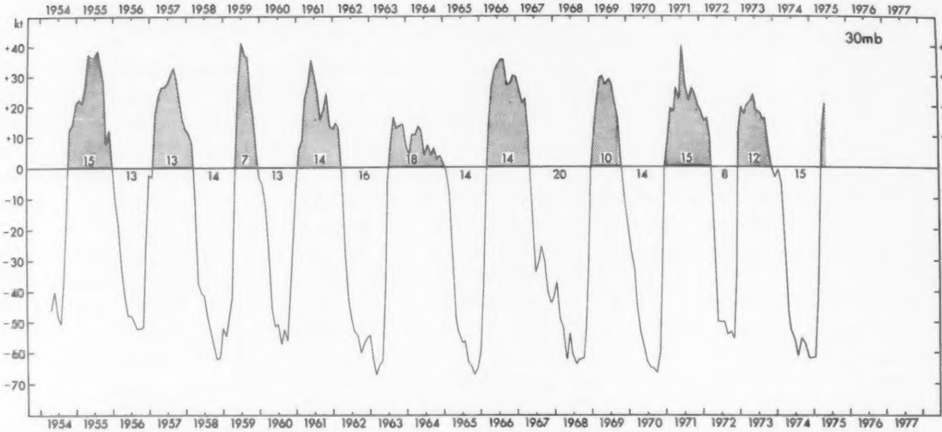

Figure 4. 30 mb monthly mean zonal wind components at Canton Island (Pacific) to 1967, then at Gan (Indian Ocean). After Ebdon (1975). Components towards the east are positive and stippled. Figures along the zero line indicate the duration, in months, of westerlies or of easterlies.

Figure 5. MSL pressure anomaly from 1951–70, July average. Mean of eight Julys with quasi-biennial oscillation at 30 mb. (After Ebdon 1975.)

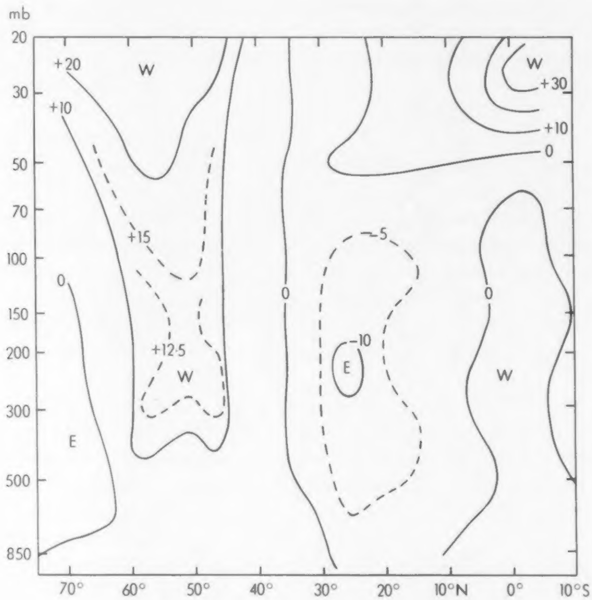

Figure 6. Vertical cross-section at 80° W showing differences between zonal wind component during westerly and easterly phases of the quasi-biennial oscillation at 30 mb in January. (After Ebdon 1975.) Speeds in m s^{-1}.

in phase but the effect is weaker at 1000 mb. It must be emphasized that these observations of quasi-biennial oscillations outside the tropical stratosphere have only been associated statistically with the tropical stratospheric quasi-biennial oscillation at this stage. Physical associations have not been established.

(d) *Teleconnections*

Interannual variations in the atmosphere are sometimes coherent on very large scales. In fact, events at locations in differing regions of the globe have often been found to be statistically connected in the sense that opposite effects tend to occur at distant places (the effects are negatively correlated). An important example of such a 'teleconnection' is the Southern Oscillation, documented by Walker and Bliss (1932) as an inverse but non-periodic pressure variation on interannual time-scales between the east Pacific Ocean and the east Indian Ocean at low latitudes. The major northern hemisphere long-distance relationships are summarized for winter in Fig. 7, from Wallace and Gutzler (1981), in which negative correlations are indicated between locations at opposite ends of the arrows. The variations are not periodic. Of particular interest are the North Atlantic oscillation, which is an inverse variation of the pressure in the Azores anticyclone and the Iceland low, a similar effect in the western North Pacific, and a negative correlation between pressure in the Aleutian low and over the northern Rockies, forming a link in a chain of events tenuously connecting the tropical Pacific with the Atlantic. The fluctuations in the Iceland low result in inverse variations ('seesaw') in winter temperature in Greenland and northern Europe (Van Loon and Rogers 1978). The pattern of teleconnections over the east Pacific and America

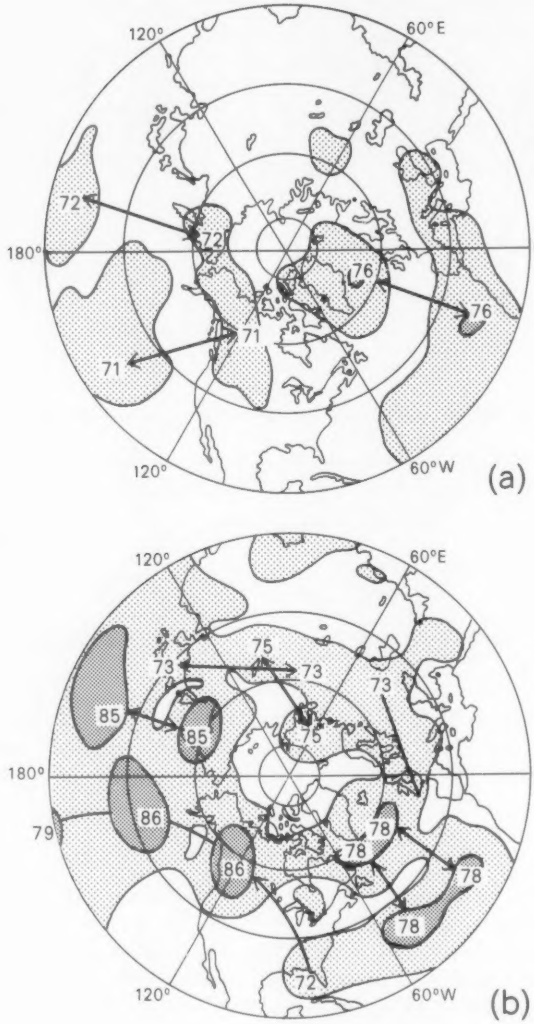

Figure 7. Strongest negative correlation p_i with any point, plotted at the base grid point for (a) sea level pressure and (b) 500 mb geopotential. Based on 45 winter months (Decembers, Januarys and Februarys) for 1962–63 to 1976–77. (After Wallace and Gutzler 1981.) Negative signs have been omitted and correlation coefficients multiplied by 100.
Regions where $p_i < 60$ are unshaded, where $60 \leqslant p_i < 75$ stippled lightly, where $75 \leqslant p_i$ stippled heavily.
Arrows connect centres of strongest teleconnection.

in Fig. 7(b) is reminiscent of the wave-trains resulting from subtropical thermal and orographic forcing in the five-layer baroclinic model of Hoskins and Karoly (1981), whose results may also throw light on the relationships between the Southern Oscillation and interannual variability in mid-latitudes, discussed in the next section.

3. Hypotheses for interannual variability

There are at least three classes of explanation of atmospheric interannual variability: interactions within the atmosphere, whereby short-period fluctuations create and maintain longer-term equilibria; thermal interactions with the oceans and cryosphere (ice and snow); and external forcings. The last group of theories will not be discussed here: it includes the influence of variations in solar constant, which has, however, hitherto been very difficult to measure to the required accuracy, and the influence of volcanic dust. In the present paper, internal atmospheric interactions will be discussed in the context of the tropical stratospheric quasi-biennial oscillation and atmosphere–ocean interactions will be illustrated by an examination of the Southern Oscillation.

(a) *Interactions within the atmosphere: the quasi-biennial oscillation*

Holton and Lindzen (1972) have formed a hypothesis that the downward-propagating quasi-biennial oscillation in the tropical lower stratosphere is driven by vertical convergence of the momentum flux of radiatively dissipating, vertically propagating, short-period (5–15 days) waves excited in the upper troposphere. The radiative dissipation results from reduction of the amplitude of the temperature cycle of the wave by Newtonian cooling.

Imagine an atmosphere initially at rest until waves of a type which propagate westerly momentum upwards are excited near the tropopause, as a result of e.g. geographically irregular tropospheric heating. Equatorial 'Kelvin waves' have the appropriate properties, propagating eastwards as well as upwards. The waves will propagate upwards with weak attenuation up to near 30 km (10 mb) where, because the radiative dissipation increases with height, their amplitude will decrease rapidly with height, leading to a rapid reduction with height in the upward westerly momentum flux associated with the waves, and hence to a westerly acceleration of the mean flow. As a result there will be a reduction of the eastward phase speed relative to the mean flow. If the acceleration of the mean flow is slow compared with the accelerations involved in the wave motions, linear approximations will apply and it can be assumed that the vertical phase speed of the waves will be reduced in proportion to the horizontal phase speed. The reduced vertical phase speed will allow more time for Newtonian cooling to reduce the wave amplitude; in other words there will be increased radiative dissipation of the waves where they encounter the westerly flow, i.e. in the shear zone beneath the strongest westerly flow. The resulting decrease of wave amplitude with height will lead to convergence of the wave momentum flux at these lower levels. The momentum will no longer be available for the upper levels, where the acceleration will therefore decrease. However, the increased acceleration at the lower levels will lower the shear zone, further lowering the level at which most of the momentum flux converges. Eventually a westerly shear zone will descend to near the tropopause where a balance will be established between convergence of wave momentum and vertical diffusion of momentum into the troposphere.

Now imagine that waves which propagate easterly momentum upwards are also excited near the tropopause; such waves are also observed in the tropics. These waves will be able to propagate through the westerly shear zone but, as a result of radiative dissipation at higher levels, their easterly momentum flux will converge there, so that, in a manner similar to that described above, a downward-propagating easterly shear zone will follow the westerly shear zone. Eddy diffusion will permit the easterly shear zone to propagate to the tropopause without leaving a shallow layer of westerlies.

Holton and Lindzen illustrated their hypothesis with a one-dimensional analytical model, which also included an imposed climatological mid-stratospheric tropical semiannual oscillation of zonal wind. Their results are presented in Fig. 8. The downward propagation and periodicity (27 months) are similar to what on average is observed, but the periodicity could have been varied by altering the radiative dissipation rates, or by changing the wave amplitudes at the lower boundary. However, their values for these parameters were all compatible with observations, lending credibility to their theory. The semiannual oscillation may be responsible for the synchronous nature of the quasi-biennial oscillation throughout the tropics because, by affecting wave phase speeds and thus momentum convergence in the 30–40 km layer, it could limit the possible times of onset of new shear zones. However, the semiannual oscillation is not essential to Holton and Lindzen's theory and they did not regard it as determining the time-scale of the quasi-biennial oscillation.

Plumb (1977) has suggested modifications to Holton and Lindzen's theory. In particular, because the wave amplitude and therefore the momentum convergence at a given level are controlled by the mean flow at lower levels, he found the vertical variation of radiative cooling to be unnecessary. Also, Plumb found that the destruction of the lowest zone was a result of eddy diffusion of momentum from the zone of reverse winds immediately above, rather than eddy diffusion into the troposphere.

The mechanisms by which the tropical lower stratospheric quasi-biennial oscillation affects the rest of the atmosphere are still uncertain. It is possible that the associated temperature changes near the tropical tropopause may affect the strength of the convection, and thereby influence the Hadley cell and subsequently the rest of the circulation (Folland, private communication).

(b) *Atmosphere–ocean interactions: the Southern Oscillation*

The Southern Oscillation has already been referred to as an inverse variation of pressure between the Indian and Pacific Oceans in the tropics. Fig. 9 shows the global scale of the phenomenon and Fig. 10(c), in which a positive index denotes above-normal pressure over the tropical south-east Pacific, shows that the fluctuations are irregular in time but occur on time-scales of the order of several years. However, Figs 10(a), (b) and (d) also show the involvement of winds, sea surface temperatures and rainfall in the equatorial Pacific. When pressure is higher than normal over the tropical south-east Pacific there is enhanced easterly flow along the equator in mid-Pacific, accompanied by reduced sea surface temperatures and reduced rainfall. There is also an enhanced westerly return flow aloft (Julian and Chervin 1978) completing a direct circulation in an equatorial plane, known as a 'Walker cell'. According to Bjerknes (1966), the reduced sea surface temperatures are a result, not mainly of westward advection of water from the cold Humboldt Current, but largely of enhanced upwelling of water as a result of the wind-induced Ekman drift: persistent easterlies result in poleward motion of surface water in geostrophic equilibrium, and the consequent equatorial divergence can be balanced only by equatorial upwelling. The rainfall in the equatorial mid-Pacific is reduced, partly because of suppression of local convection over the cooler ocean, and partly because of subsidence associated with the large-scale vertical circulation (Bjerknes 1969). At the opposite stage of the Southern Oscillation cycle pressure is lower than normal over the tropical south-east Pacific, with reduced mid-Pacific equatorial easterlies, increased mid-Pacific rainfall and increased eastern and mid-Pacific sea surface temperatures. Horel and Wallace (1981) have also shown that the entire tropical troposphere is warmer at this stage of the Southern Oscillation. It is thus an important phenomenon on a global scale.

Bjerknes (1969) considered either stage of the Southern Oscillation to be self-amplifying. For example, an increase in the pressure difference is associated with an increase in the easterlies, leading to a reduction of the sea surface temperatures in the central and eastern equatorial Pacific and hence to an increase of east–west temperature contrast, so that the Walker direct cell is strengthened, giving a further

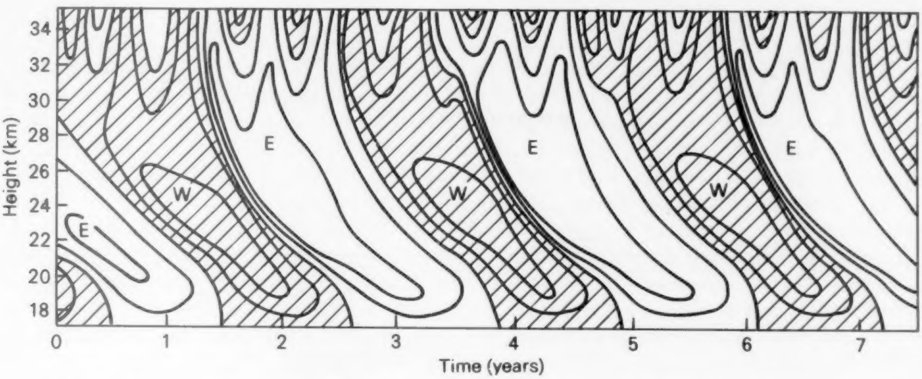

Figure 8. Time-height cross-section of mean zonal wind. After the model of Holton and Lindzen (1972). Isopleths are drawn at 10 m s^{-1} intervals.
Regions of westerly flow are shaded.

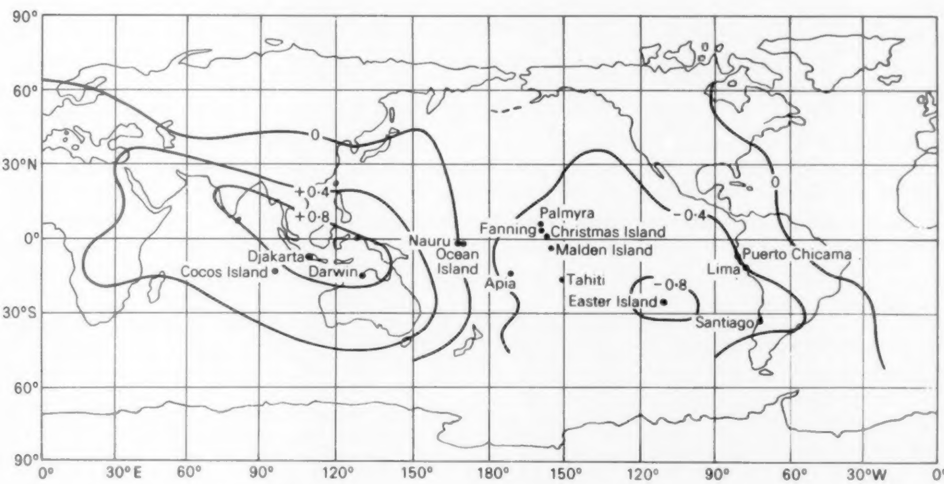

Figure 9. Schematic map (after Berlage 1966) showing isopleths of correlation of monthly mean station pressure with that of Djakarta, Indonesia.

increase in pressure difference and stronger winds, and so on. But in his 1969 paper Bjerknes was unable to specify the means of turnabout between opposite stages of the Southern Oscillation. In his 1966 paper, however, he had proposed the well-known hypothesis that an anomalously warm ocean surface would provide extra energy to the north–south (Hadley) circulation at that longitude. It would follow (Julian and Chervin 1978) that not only the subtropical westerly jet but also the low-latitude, low-level easterlies would increase, the equatorial ocean would cool, and so the Southern Oscillation would change to its opposite phase. However, the cool ocean would now be a reduced energy source for the

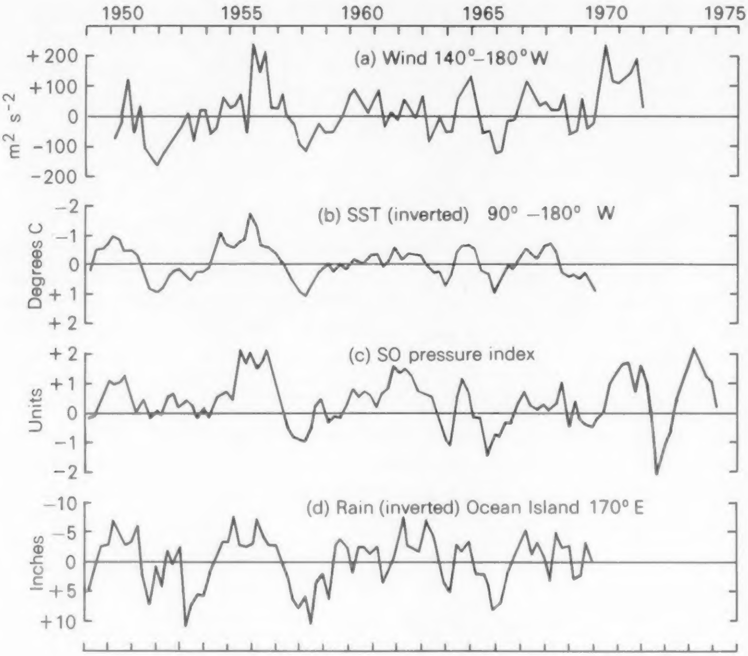

Figure 10. Parameters of the Southern Oscillation (after Wright 1977).
(a) Zonal component of wind stress, 4°N–4°S, 140°W–180°W, seasonal anomalies relative to 1950–69 mean (after Wyrtki 1975).
(b) Sea surface temperatures, 10°N–10°S, 90°W–180°W, seasonal anomalies relative to 1949–69 means.
(c) Southern Oscillation seasonal pressure index.
(d) Rainfall at Ocean Island, 0°52′S, 169°35′E, mean monthly anomalies for each season relative to 1950–69 mean.
Ticks along the top and bottom margins denote northern autumn of the year immediately preceding.

Hadley circulation, which would weaken, giving reduced low-latitude easterlies and a warming of the equatorial ocean, so that the Southern Oscillation would have come full circle.

If the above chain of reasoning were correct there would be a lag, on the time-scale of atmospheric circulation changes, i.e. days or weeks, between the time of warmest ocean and the time of strongest easterlies. Fig. 10 does not support this; the strongest equatorial easterlies appear to occur towards the end of periods with cold ocean. Wyrtki (1975) therefore proposed a different hypothesis to explain the changeover of the Southern Oscillation from positive index (strong winds, cold ocean) to negative (warm ocean). On the basis of sea-level observations from coastal and island stations, he suggested that the increased easterlies in the cold-ocean phase can strengthen the South Equatorial Current and thereby maintain an anomalous slope of sea level, upwards towards the west. But within a few months of a weakening (for an unspecified reason) of the winds, the accumulated warm water will move east from the west Pacific and the thermocline will be lowered, so that the remaining winds will be unable to cause upwelling of cold water, even though there is some evidence that upwelling is at least as intense at this

stage (Anderson 1981). Thus the warm-ocean phase will be established. The warming occurs only during northern winter and Wyrtki also showed that the same phenomenon occurs in a less intense form during every northern winter. He did not attempt to explain the mechanism of reversion to the cold-ocean phase of the Southern Oscillation. Neither does Wyrtki's hypothesis appear to explain the fact (Horel and Wallace 1981) that the equatorial central Pacific warms several months later than the Peruvian coastal waters. Barnett's (1977) statistical study lends support to Wyrtki's hypothesis so far as the eastern equatorial Pacific is concerned, and then favours westward advection of less-cool water and reduced wind-induced equatorial upwelling, as reasons for the later mid-Pacific warmth.

Despite the inadequacy of Bjerknes's hypothesis in explaining the turnabouts of the Southern Oscillation it has been shown, in agreement with his hypothesis, that the annual mean strength of the northern hemisphere subtropical jet stream in the longitude range of interest increases as the eastern equatorial Pacific warms (Julian and Chervin 1978). In addition (Van Loon and Rogers 1981) the characteristics of the winter northern hemisphere mid-latitude circulation are changed, with increased heat transport in the quasi-stationary eddies, lower mean temperature between 30°N and 60°N, and heat transport by transient eddies reduced north of 45°N but increased south of 45°N. Similar adjustments of the mid-latitude long waves appear in the steady-state linearized primitive-equation model of Hoskins and Karoly (1981) when a subtropical forcing (heat source) is introduced. These and other theoretical results also indicate that strong teleconnections to mid-latitudes are possible only when the upper tropospheric westerlies extend over the low-latitude heat source. For the northern hemisphere mid-Pacific this condition is fulfilled only in the winter half-year and the observational evidence indeed suggests that the strong teleconnections with mid-latitudes occur only in winter.

4. Conclusion

Future investigation of large-scale interannual variability of climate requires observational and modelling studies of atmospheric and oceanic aspects. Modelling studies may in some cases be in simple forms for testing specific hypotheses, as in the quoted work on the quasi-biennial oscillation, but many phenomena appear to require fully fledged models for adequate representation. In the particular case of the Southern Oscillation, an interactive ocean–atmosphere model would be of considerable value in investigating what has turned out to be a highly complex and intriguing phenomenon.

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The forecasting of state of sea

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(Meteorological Office, Bracknell)

Summary

The requirement for, and history of, state-of-sea forecasting in the Meteorological Office are briefly described, together with a summary of the present operational forecasting system. The various forms of output from the system are discussed and some examples are given of the applications to which they are put. The results of some verification exercises are also examined.

1. Introduction

A firm need for a state-of-sea forecasting service has been established over the last 10 years, principally because of the growing offshore industry in the North Sea, but also as a result of economic pressures on shipping lines and an increasing general requirement for greater safety margins in all aspects of marine activity.

The Meteorological Office is currently satisfying the need for such state-of-sea forecasts because of a unique coincidence of necessary skills, information and facilities. The wind fields that are forecast by the numerical weather prediction models provide the necessary forcing functions that enable a state-of-sea forecast to be made for a wide area and a long forecast period. The wide experience of numerical modelling of physical systems that is found in the Office has been fruitfully turned to designing an operational state-of-sea forecasting model which incorporates the known physical processes which govern the behaviour of the sea surface. The combination of powerful computing resources and a centralized telecommunication system provides an environment where the necessary complex mathematical modelling can be efficiently carried out and the required products and information quickly distributed to the users.

Before the advent of powerful computer technology the accepted means of state-of-sea forecasting was by way of empirical wave-growth curves, deducing the wave height in terms of wind speed, duration and fetch. The numerical model in use by the Office incorporates in more stringent formulations the essential physical principles which underlie such empirical techniques. Details of the physical basis of the current models are to be found in the Appendix; it is sufficient here to summarize the basic processes which are modelled. Recent theoretical and experimental work by oceanographers in many countries has greatly increased the degree of knowledge of the processes involved in wind-wave generation and dissipation. The model in use incorporates such processes as wave growth, interaction and dissipation, the advection of swell energy and, in the higher-resolution version, such depth-dependent processes as refraction and bottom friction.

2. The operational system

The current operational state-of-sea forecasting services are based on the products of two numerical models which are run on the IBM 360/195 computer following the twice-daily integrations of the atmospheric prediction models. Like the atmospheric models the state-of-sea models consist of a coarse-mesh and a fine-mesh version, using winds from the appropriate atmospheric model. The coarse-mesh version covers the North Atlantic and North Pacific Oceans down to 18°N with an approximate grid resolution of 300 km in mid-latitudes (Fig. 1). The fine-mesh model has a more limited area, the continental shelf and north-eastern Atlantic, with a resolution of 50 km (Fig. 2). The winds for this model are interpolated from data on the fine-mesh atmospheric model grid. The coarse-mesh model is

run for a forecast period of 48 hours and provides boundary values for the fine-mesh model; i.e. swell forming in the Atlantic is passed into the continental shelf model and advected onward. The shelf model runs for a 36-hour forecast period.

Output from the models is usually in chart format, showing significant wave-height contours for either swell or total seas (Figs 3 and 4). Information is also available on wave periods. Some products are in the form of grid-point data, either assembled into WMO grid code for many points for onward transmission or listed in tabular form as a printout (Fig. 5).

Before running each forecast a 12-hour 'hindcast' is performed. This is essentially a repeat of the first 12 hours of the previous integration but this time using wind fields that are updated either with observations or with analysed products from the atmospheric models. This process ensures that the starting point of each state-of-sea forecast is the best possible description within the limits of the numerical simulation technique. These hindcast fields are kept in an archive, currently containing three years of acceptable data. At present no wave observations go into the models as data during the hindcast run.

The use of observed wave data, whether as visual estimates or measured values, is confined to the area of validation. Some detailed figures are given in Table I. A data set of forecast values for a greatly reduced number of grid points is retained during operational runs, so that at the end of each month a validation exercise can be carried out. Included in Table I are the corresponding errors of the forecast

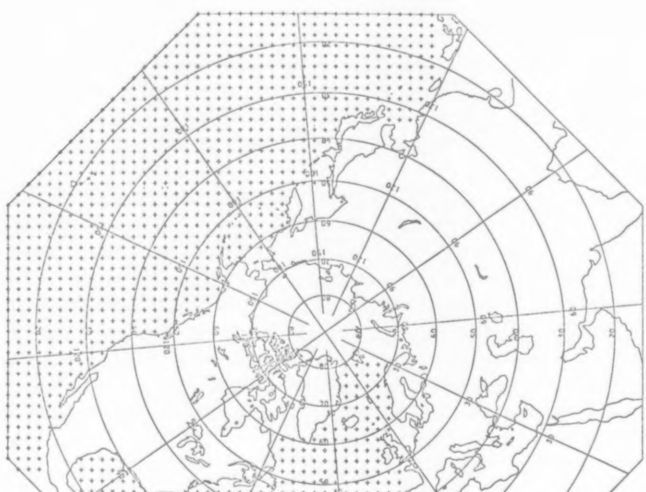

Figure 1. Grid points of the coarse-mesh wave area.

wind field at the same locations. Not surprisingly there is a good correlation between higher forecast wind errors and higher errors in forecast significant wave height. The scatter in the relationship is due to the differing proportions of 'local wind sea' and 'advected swell' components of the total significant wave height at different locations. The lowest root-mean-square errors of wave height for given wind errors are found at Penzoil, at the southern end of the North Sea, where incoming swell is a minor constituent. The worst errors are found at Ocean Weather Station 'L' where incoming Atlantic swell is very important and perhaps not simulated well enough by the coarse-mesh model which provides the boundary values.

3. Applications

The different resolutions of the two models, together with the depth-dependent effects found only in the fine-mesh versions, reflect the potential uses for the model products. The use of the coarse-mesh products is confined to shipping activities, hence a chart format is the most suitable output medium. A forecaster in the Central Forecasting Office (CFO) has the responsibility of preparing 24-hour and 48-hour forecast charts of total significant wave height for the North Atlantic. These charts are produced by modifying the products of the coarse-mesh wave model in the light of the expected differences in wind-field evolution from the forecast values given by the coarse-mesh numerical weather prediction model,

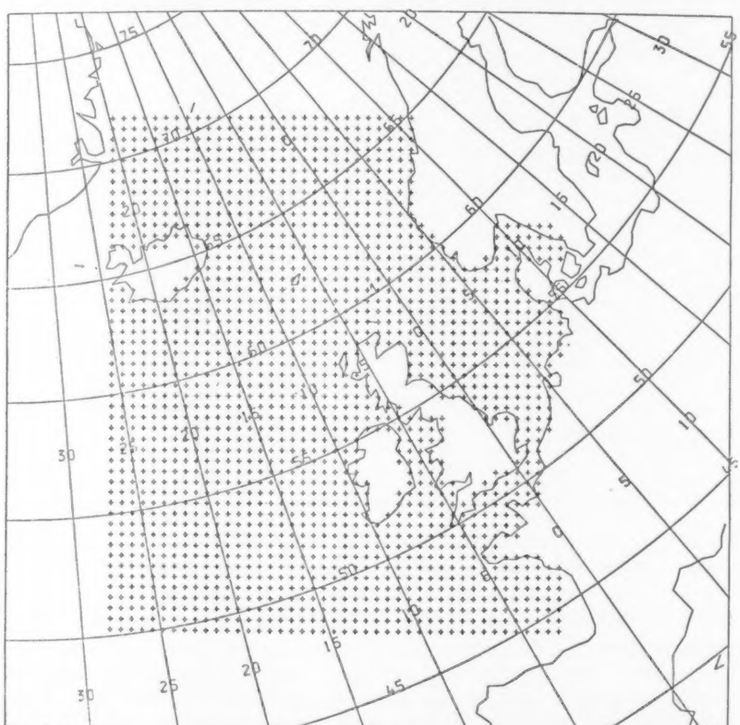

Figure 2. Grid points of the fine-mesh wave area.

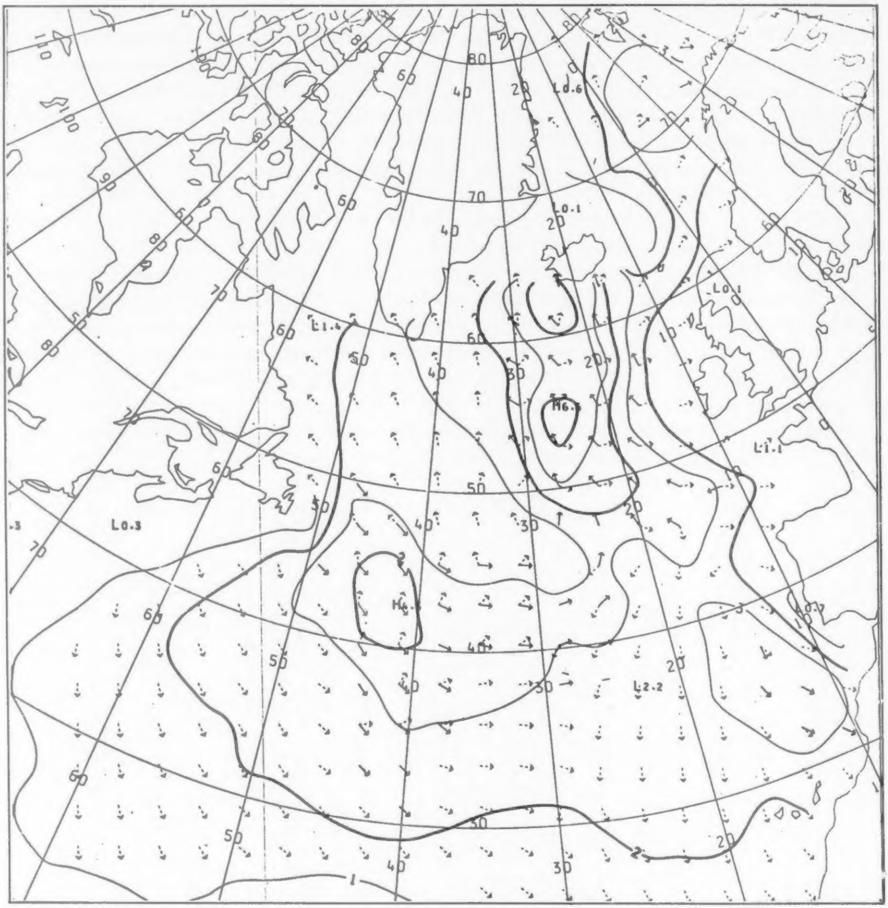

Figure 3. Example of output from state-of-sea model in chart format. Sea and swell contours for 12 GMT on 4 November 1980. Arrows indicate wind direction. Dotted arrows indicate swell direction.

using the forecaster's experience of the relationship between broad-scale wind fields and the associated wave developments in the model. The final product is hand drawn and then broadcast by means of radio facsimile. The Ship Routeing Service also uses the amended North Atlantic chart and, following discussions with CFO forecasting staff, makes use of forecast wave products for the North Pacific. Occasionally, special runs of a Mediterranean sea wave forecast model are made when the Ship Routeing Service requires such information. The cost of running these models forms an element of the fees charged for the complete routeing service. For conventional vessels the object of the service is to select the best route for the ship to follow in order to reach her destination in the shortest possible time, with the most economical fuel consumption, commensurate with least damage to ship and cargo. Wave

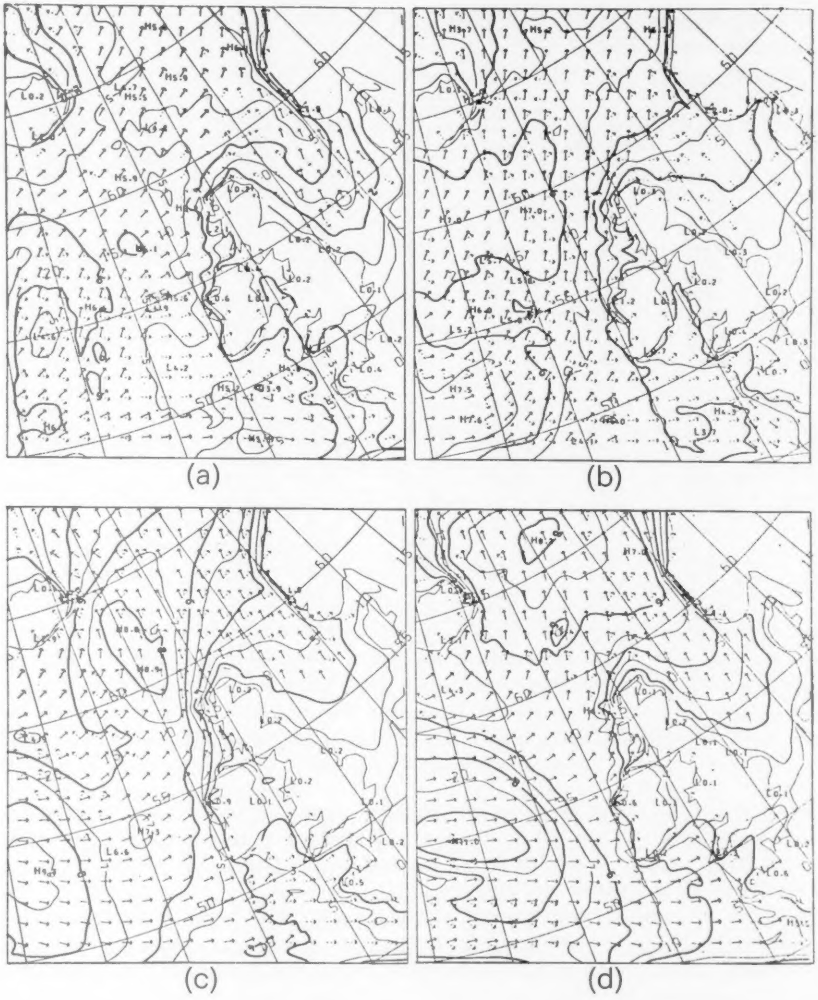

Figure 4. Example of output from state-of-sea model in chart format, showing sea and swell contours, wind direction (arrows) and swell direction (dotted arrows).
(a) Starting point of forecast at 00 GMT on 7 March 1982.
(b) 12-hour forecast.
(c) 24-hour forecast.
(d) 36-hour forecast.

FOR TRANSMISSION TO SOUTH WEST WATER AUTHORITY VIA MET.O.5 PAGE 1

INITIAL DATA TIME 12Z 7/ 2/82

LOCATION 50.3N 3.6W

HOURS AFTER DATA TIME	WIND SPEED KTS	WIND DIRECTION DEG(FROM)	TOTAL WAVES HEIGHT M	TOTAL WAVES PERIOD SECS	WIND SEA HEIGHT M	WIND SEA PERIOD SECS	SWELL HEIGHT M	SWELL PERIOD SECS	SWELL DIRECTION DEG(FROM)
0.0	6.8	205.	1.7	6.6	0.3	0.1	1.6	7.1	233.
3.0	12.2	227.	1.6	6.6	0.6	3.6	1.5	7.9	235.
6.0	17.9	236.	1.6	6.2	0.9	3.9	1.3	8.8	236.
9.0	20.6	254.	1.5	6.2	0.9	4.1	1.2	8.4	231.
12.0	24.0	262.	1.4	6.2	0.8	3.9	1.2	8.1	231.
15.0	20.7	264.	1.4	6.2	0.8	4.0	1.2	8.0	232.
18.0	18.5	277.	1.4	6.2	0.6	3.7	1.2	7.4	230.
21.0	13.2	239.	1.4	6.5	0.4	3.1	1.4	7.1	231.
24.0	19.9	223.	1.6	6.3	0.8	4.0	1.3	8.1	231.
27.0	26.6	227.	2.0	6.2	1.6	4.8	1.2	9.0	224.
30.0	26.0	224.	2.5	6.3	2.3	5.5	0.9	10.0	220.
33.0	27.6	228.	2.8	6.5	2.5	5.8	1.2	9.9	218.
36.0	26.7	221.	3.1	6.7	2.6	6.2	1.7	9.8	215.

LOCATION 49.8N 4.8W

HOURS AFTER DATA TIME	WIND SPEED KTS	WIND DIRECTION DEG(FROM)	TOTAL WAVES HEIGHT M	TOTAL WAVES PERIOD SECS	WIND SEA HEIGHT M	WIND SEA PERIOD SECS	SWELL HEIGHT M	SWELL PERIOD SECS	SWELL DIRECTION DEG(FROM)
0.0	8.8	222.	3.1	8.2	0.5	2.8	3.1	8.7	260.
3.0	14.2	244.	3.0	8.1	0.7	3.6	2.9	8.9	261.
6.0	17.8	243.	2.9	7.4	1.8	5.6	2.2	10.7	266.
9.0	20.3	256.	2.8	7.0	1.7	5.0	2.2	10.1	263.
12.0	24.1	261.	2.8	6.8	2.2	5.6	1.8	10.8	264.
15.0	21.4	261.	2.8	6.8	2.6	6.6	1.2	11.8	269.
18.0	19.3	272.	2.7	6.7	2.2	6.0	1.6	10.4	259.
21.0	15.4	242.	2.7	6.9	1.7	4.8	2.1	9.2	256.
24.0	20.8	226.	2.7	7.0	2.5	6.5	1.1	11.9	265.
27.0	25.6	227.	3.0	6.6	2.6	6.2	1.5	10.5	253.
30.0	25.6	222.	3.3	6.8	3.2	6.9	1.1	11.9	262.
33.0	26.6	223.	3.6	6.9	3.4	7.1	1.1	12.0	257.
36.0	26.6	221.	3.9	7.2	3.9	8.0	0.5	13.7	269.

Figure 5. Example of output from state-of-sea model in tabular form.

conditions as well as wind are an important consideration in such an exercise since average speed over the route as well as stability is a function of state of sea. Non-conventional requests, such as for tows, may have more restrictive state-of-sea limitations and advice can be given on weather and state-of-sea 'windows' during which movements are possible.

Products of the fine-mesh continental shelf model are used for a wider variety of purposes. The forecast products are used extensively by staff at London Weather Centre where the greater part of the forecasting service for the offshore gas and oil industries takes place. Both charts (Fig. 4) and grid-point digital data go to London Weather Centre where, by a judicious synthesis of up-to-date analyses, numerical forecasts and empirical techniques, forecasts of state of sea are derived for transmission to users. Some basic forecast data are also sent direct to staff at Aberdeen, Kirkwall and Lerwick. The staple product for the offshore industry is significant wave height but some operations, such as the placings of large modules, are also sensitive to particular wave periods. The formulation of the forecast models enables primary energy-containing periods in the frequency spectrum to be identified, thus allowing forecasters to give an informed opinion of whether such sensitive operations should be planned during the forecast period. The expansion of forecasting services to the offshore industry is, however, hampered by difficulties in telecommunication, a restraint which at present severely affects forecasters

Table I. *Forecast errors of fine-mesh wind speed and significant wave height.*

Station	Forecast time (hours)	Wind speed ($m\ s^{-1}$) N	Mean	RMS	Wave height (m) N	Mean	RMS
OWS 'M'	+12	1234	−2.0	3.8	1228	0	1.1
64.8°N, 3.2°E	+24	1233	−2.3	4.2	1227	0	1.2
	+36	1230	−2.5	4.7	1224	−0.1	1.3
OWS 'L'	+12	1229	−1.0	3.8	1218	0	1.4
57.1°N, 19.7°W	+24	1228	−1.3	4.2	1216	−0.1	1.5
	+36	1225	−1.5	4.7	1212	−0.2	1.5
Penzoil	+12	1091	0	2.7	1022	0	0.5
53.2°N, 3.2°E	+24	1088	0.1	2.9	1022	0	0.6
	+36	1086	0	3.3	1020	0	0.6
Statfjord	+12	1051	0.1	2.7	880	−0.2	0.8
61.2°N, 1.8°E	+24	1052	−0.1	3.6	879	−0.2	1.0
	+36	1049	−0.2	3.9	877	−0.2	1.1
Data Buoy 1	+12	1045	0.2	2.9	988	0.1	0.9
48.7°N, 9.0°W	+24	1043	0.1	3.1	985	0.1	1.0
	+36	1044	−0.2	3.4	985	0	1.0

Data from June 1980 to February 1982.
N = Number of occasions. RMS = Root mean square.

deployed offshore at the sites of operations. A tailored service in terms of wave height, period and direction could be supplied, given adequate communications. Other users of forecast state-of-sea data from the fine-mesh model are those water authorities with responsibility for some aspects of coastal defence. At present four such authorities receive forecast state-of-sea information, once or twice a day, for locations along their coastline. The data are usually in a tabular form (Fig. 5) giving forecast information at 3-hour intervals. This service was initiated following the Portland flooding of February 1979 and usually runs from September to April. A comparison between hindcast wave heights and measured data in Lyme Bay is given in Fig. 6. The correlation is quite acceptable, bearing in mind that the hindcast model data are available only at 12-hour intervals, i.e. that absent maxima are not necessarily unpredicted, and also that the wave rider buoy concerned was only 100 m or so from the beach. The model purports to represent open-sea situations.

The archive of hindcast states, or diagnoses, has been used quite extensively in a variety of ways. The major application has been as an aid to the Wave Energy Steering Committee of the Energy Technology Support Unit. The archive has been interrogated to give an additional estimate of the long-term average wave energy resource, both off the Hebrides and in the western approaches. The agreement between short-period averages given by the model and by wave rider buoy measurements was extremely close. Other applications of the diagnostic archive have been also mainly climatological in nature, principally for the Hydraulics Research Station, but there have been interesting oddities like the ecology of East Yorkshire beaches and the estimated state of sea in which a ship was abandoned by its crew!

The models have also been used in less conventional ways in order to meet commercial research and development requirements. Both Marex Ltd and the United Kingdom Offshore Operators Association have placed contracts with the Office for the state-of-sea models to be run under specified wind-field conditions. Such special projects have earned £28 000 since 1980. The income from routine services is

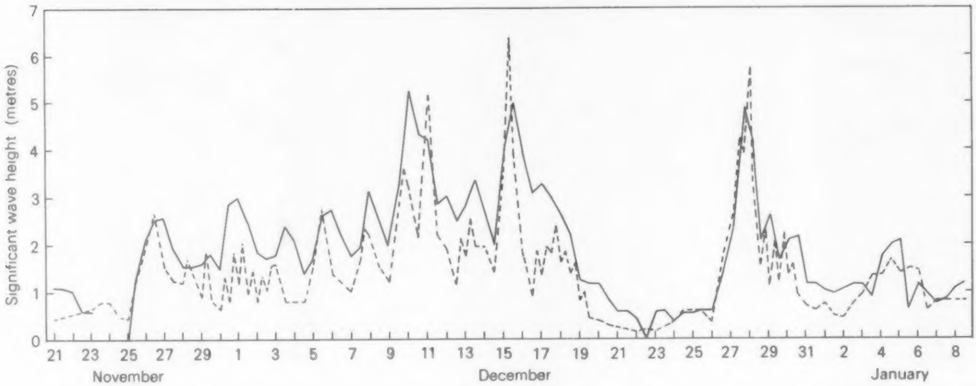

Figure 6. Comparison between hindcast wave heights and measured data in Lyme Bay (50.5°N, 2.6°W) for the period from 00 GMT on 21 November 1979 to 12 GMT on 8 January 1980.
——— Hindcast data. - - - - Measured data.

harder to quantify since both the London Weather Centre and the Ship Routeing Service charge a fee which incorporates all aspects of costs for services rendered. All that can be said is that the level of business for both organizations is constantly rising and that the availability of forecast state-of-sea data is a significant added feature in promotional exercises. Directly raised charges, i.e. for services to water authorities, the Energy Technology Supply Unit, the Hydraulics Research Station etc., stand now (1981–82) at £10 000 a year.

4. Future development

The acquisition of the CYBER 205 computer provides the opportunity for the state-of-sea forecasting service to be re-examined and assessed with respect to known requirements and possible expansion. The models themselves can be improved, both by means of better forecast wind fields (products of the new numerical weather prediction models), higher resolution in space, spectral frequency and direction, together with the incorporation of improvements to the simulation of some of the physical processes represented in the models.

The increased processing power of the CYBER will allow the resolution improvements referred to above, but it will also make possible an expansion of geographical coverage. This increase in area covered by the models will overcome existing deficiencies as well as lending extra promotional weight to the Ship Routeing Service. Specifically, a tropical ocean model will provide trade-wind swell input to the northern ocean areas, a feature notably lacking in the current models.

Wider coverage introduces the problematic question of validation of forecasts against reliable data. To cover this need the Office is maintaining an interest in state-of-sea measurement by means of high-frequency radar from land stations and by remote sensing from satellites. Such measurements also lead to estimates of wind speed and direction over the sea surface, another very promising source of information in areas of sparse data.

Appendix: Brief description of wave model

The basis of the operational state-of-sea forecast models is a statistical representation of the wave field, rather than an array of discrete values representing individual waves. The spectrum as represented is a function of the variance distribution of the surface elevation; hence such features as significant wave height and a representative wave period can be arrived at by means of the ratio of the appropriate moments of the spectrum at a point.

The point representation is made up of 12 directions (i.e. at 30° intervals) and 11 spectral frequencies ranging from 0.05 to 0.308 Hz (i.e. from 20 to 3.25 seconds period). Thus a sum of very short to very long waves can be assembled for each direction totalling 132 values for each grid point. The models function by considering the evolution of each spectral component through the forecast period, an evolution controlled by physical processes which have varying degrees of effect depending on the specified frequency and direction.

The rate of change of the magnitude of each component during a model time-step can be split into the contribution of individual processes:

(a) *Propagation.* Energy is moved from one part of the wave field to another. In deep water this process occurs without change of direction or speed. Speed of advection is inversely proportional to the frequency of the component.

(b) *Refraction.* As water shallows, the direction and speed of propagation change, following Snell's law. An important effect in the fine-mesh model.

(c) *Growth and decay.* In response to wind forcing, wave initiation and growth take place. Initial wave growth is linear but this stage is rapidly succeeded by an exponential growth stage up to a limit dependent on local wind speed. As waves become too steep they break, resulting in an energy loss; this process is also modelled. Initial growth, and decay through 'white capping', are essentially higher-frequency effects.

(d) *Non-linear interaction.* An internal redistribution of energy between neighbouring frequency components. Observations show that wave energy tends to migrate to lower frequencies than those which are fed in by the wind; i.e. waves become longer.

(e) *Bottom friction.* Owing to the roughness of the sea bed, long-wave components begin to lose energy. Again this is an important effect in the fine-mesh model.

The net result of these processes in physical reality is to shape the spectrum into a form that has been extensively reported in scientific literature. The operational model is to a large degree forced into that representative spectral shape, thus preserving the correct orders of magnitude for the individual physical processes being modelled.

Note: 'Significant wave height' is the mean height of the highest third of the observed waves.

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The Meteorological Office Ship Routeing Service

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Summary

The Meteorological Office Ship Routeing Service employs a team of Master Mariners who work closely with forecasters at the Central Forecasting Office, Bracknell. Ships' performance curves are used in conjunction with forecasts of state of sea to estimate optimum routes satisfying various criteria, e.g. least time, minimum damage, maximum fuel saving, etc. Various complicating factors are briefly described as are the financial benefits to be obtained.

1. Introduction

Up to the nineteenth century ships crossing the oceans of the world could only make use of the fund of well-known climatic principles built up by their predecesors. It was not until 1852 that Lieutenant Maury of the US Navy painstakingly collected observations from ships' deck logs in order to compile a volume of recommendations of routes for vessels crossing the Atlantic.

The practice of determining the route for a ship (routeing) from a shore-based centre only became cost-effective in the post-World War II era following the introduction of efficient means of telecommunication and the use of high speed computers to predict the development and movement of weather systems. The first shore-based ship routeing centre was formed in the USA in the 1950s and this was followed by various European state meteorological services during the 1960s. The Royal Netherlands Meteorological Institute introduced a service in 1961 and the Meteorological Office, Bracknell began its service in 1968.

Although the term 'weather routeing' is sometimes used, 'ship routeing' is a more correct phrase since, although the weather is the main factor, the principles of navigation, seamanship, naval architecture, oceanography and marine engineering are also considered in selecting a particular route for a particular ship.

It might be suggested that the Master of a ship would be the best person to choose the route that his ship will follow. He can, of course, obtain climatological data, radio weather bulletins and facsimile charts, but he is a busy man and the information he can get is necessarily limited. At a meteorological centre such as Bracknell, on the other hand, the Ship Routeing Service employs a team of three Master Mariners who devote their whole time to selecting and monitoring the most advantageous and cost-effective routes for those ships which use the Service to follow. This team works alongside the Central Forecasting Office (CFO) forecasters and is provided with an up-to-date flow of analysis and forecast charts, ice information, warnings, bulletins and satellite pictures.

2. The ship routeing method

The first requirement in providing a ship routeing service for any particular ship is to determine the ship's response to the various wave fields it may meet. This is done by extracting data from the ship's deck log-book in order to construct a performance curve (Fig. 1). Next the 24-hour and 48-hour forecasts charts of total significant wave heights covering the route are obtained from the CFO forecasting staff. (See the companion paper, 'The forecasting of state of sea', page 209, for further details of the way these charts are produced.)

The forecast wave height and direction fields are then used, in conjuction with the ship's performance curve, to determine how far the vessel will travel in a 12-hour period over a number of possible courses and the end points of each of the 12-hourly tracks are joined to form a 'time-front'. From selected points

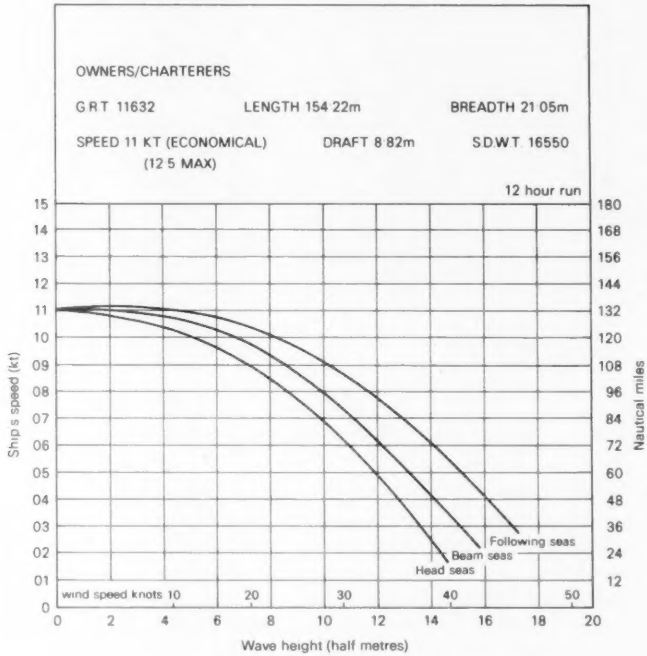


Figure 1. Example of a performance curve graph.

on this time-front the process is then repeated in successive 12-hour steps and this allows a least-time track to be calculated for that part of the route (Fig. 2). In the absence of other external factors this would normally be the course that the vessel would be advised to follow. However, at this stage, subjective consideration must be given to other parameters. The ship router has to consider a number of points, such as:

(a) Is the course navigationally feasible?
(b) Does the state of loading make the heading inadvisable?
(c) Would the time thus gained be lost through adverse currents?
(d) Would the course proposed take the vessel into an area of fog or ice?

Eventually an optimum route is selected and a message is transmitted to the Master advising him to follow the selected route. This message will also include a forecast of wind force and sea direction and height along the route.

During the course of a ship's passage this route is continued daily and the ship's progress is monitored regularly by plotting its position on successive 6-hourly weather charts. The ship maintains contact with Bracknell either by a plain-language message over telex channels or, in the case of Voluntary Observing Fleet vessels, via its 6-hourly coded weather reports.

The first part of the routeing procedure is often modified when, at the start or end of a voyage, the vessel has to pass through restricted waters such as the North Sea, the Caribbean or the Gulf of St

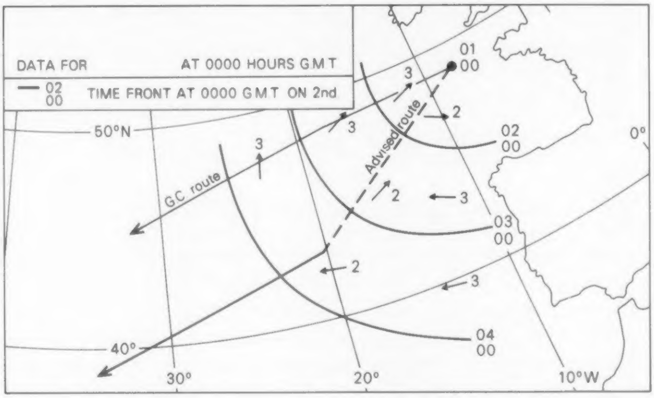


Figure 2. Calculation of least-time track; alternate time-fronts omitted for clarity.

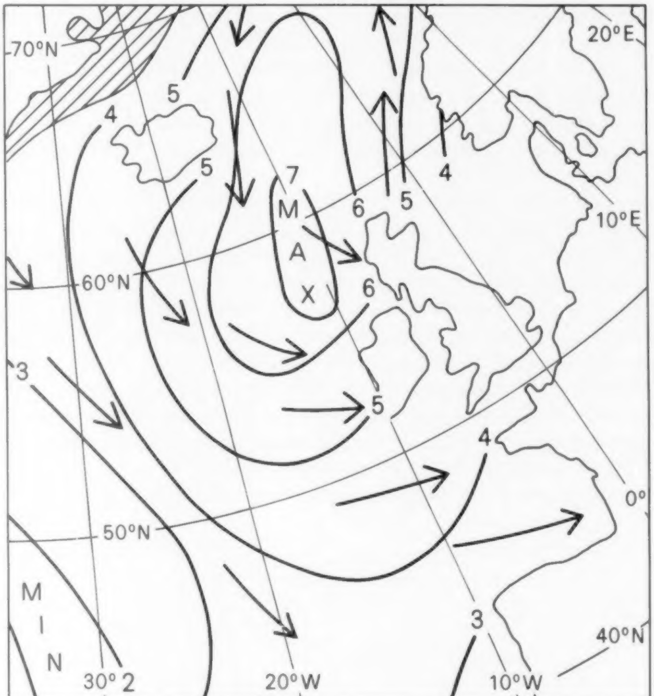
Lawrence, Canada. In these cases the important advice will concern whether the ship should proceed through one channel rather than another. For example, in one particular case a ship was due to leave Middlesbrough bound for St John's, Newfoundland loaded with steel plates. The Master was concerned about her stability and consequently it was essential that she avoided heavy weather, particularly on the beam. The wave forecasts for the period 48 hours after sailing (Fig. 3) showed heavy north-westerly seas off north-west Scotland, so the Master was advised to sail the longer route southwards from Middlesbrough and down the English Channel.

It should be noted that it is always up to the Master of the ship to decide whether to take the advice offered or whether to take an alternative route. In most cases, at the end of the passage the Ship Routeing Section plots a chart showing the forecast passage times and weather on the advised route and compares this with the calculated times and actual weather on comparison alternative routes. This chart is sent to the shipping company to allow it to assess the value of the service for itself. Fig. 4 shows such a chart, in which it is clear that a time saving of almost two days was made by following the advised southern route.

3. The aims of the Ship Routeing Service

The main aim of each routeing service will vary according to the type of ship and the requirements of the operating company. Discussions take place at an early stage between a member of the Ship Routeing Section and the company to define the problems which may arise. The following particular points are likely to be considered:

(a) *Routeing for least time on passage.* When ship routeing began the main aim was to reduce the time on passage regardless of other considerations. Nowadays, however, least-time routeings are mainly confined to oil tankers, which do not suffer cargo damage and are less susceptible to hull damage than other ships. For these ships fuel saving is the prime requirement from the Ship Routeing Service. On the basis of time saved one tanker company has calculated that during one winter of ship routeing in the Pacific an average saving of 30 hours and a total saving in fuel costs of £24 758 was achieved for a cost of £1475 on routeing fees. In the North Atlantic the same company calculated the total saving in fuel costs during the same winter to be £13 118 net.



48-hour wave forecast
valid at 0000 GMT 30 April 1975
heights in metres

Figure 3. Example of a wave forecast.

(b) *Routeing for minimum-time passage with minimum damage to hull and cargo.* In many cases the shipping company will be concerned to reduce its damage bills and the use of the Ship Routeing Service can be most effective in doing this. For example, one London company carrying paper products from Newfoundland to the United Kingdom, and employing ships liable to hull damage from pounding when in ballast, found that damage bills fell from £30 000 per ship per year to negligible amounts by using the Ship Routeing Service. The routeing charge per ship per year was about £300.

(c) *Routeing for least damage.* This is requested when the vessel is carrying a particularly sensitive cargo, such as livestock on deck.

(d) *Routeing for constant speed.* Some ship charters call for the maintenance of a certain speed over a certain time, with a financial penalty for failure. Routeing advice is adjusted to achieve this.

(e) *Routeing for fuel saving.* More recently, with escalating fuel costs, the most significant advantage of ship routeing has been in fuel saving, although this has always been a direct spin-off from least-time

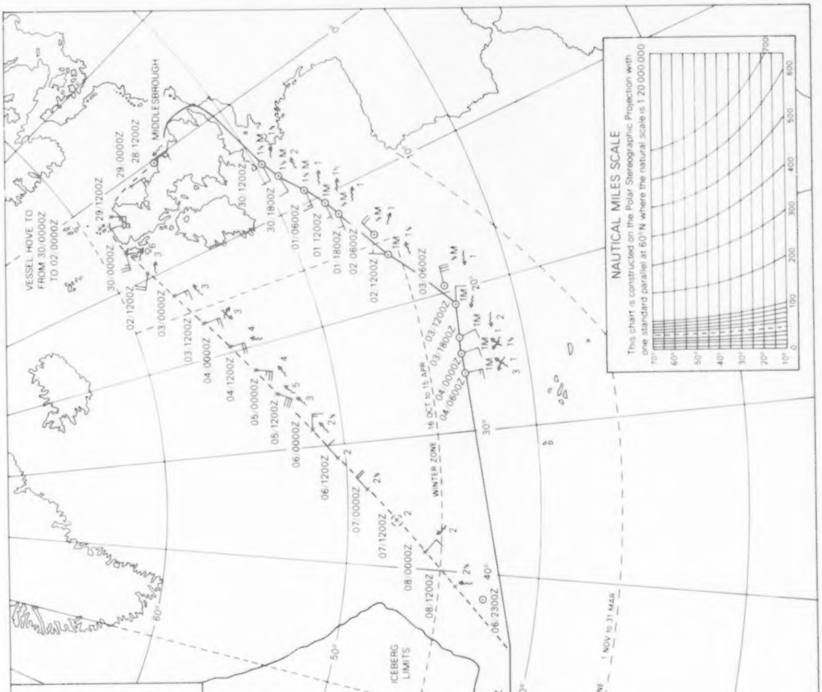


Figure 4. Example of a ship routeing chart.

or least-damage routes. The present charge for ship routeing is equivalent to about two tons of fuel for an Atlantic crossing and three tons on the Pacific, so significant savings can be made on fuel bills (as mentioned at (a) above), even in those cases where service speed has been reduced as part of the fuel economy program. It has been shown that a reduction of about 8% in fuel consumption can be achieved if the ship's engines can be run at constant power. This can be gained only if the ship is routed away from the worst of the weather. Fig. 5 is a schematic diagram showing the effects of weather on vessel operating profits.

(f) *Routeing for tows.* During the last few years the standard routeing service given by the team at Bracknell has been modified in order to give advice on the movement of oil rig and other tows, particularly in those cases where there are limiting weather factors. The standard routeing service is given only on trans-oceanic crossings, usually when eastward moving depressions are avoided by alterations of course to north or south. Where tows are concerned the ship router uses his navigational skills in conjunction with up-to-the-minute meteorological data to advise the tow operators when to sail and when and where to shelter. Recent work has included advice on the movement by barge of a steel jacket from Sardinia to Cherbourg, the towage of the Port of London Authority crane *Mammoth* from Tilbury to Greece, and the movement under tow of the Thames Barrier gates from their construction yard on Tees-side to London, at the specific request of the Chief Marine Superintendent, Cunard, who is nautical adviser for this aspect of the Thames Barrier project. More recently this type of routeing service has been requested by the insurance companies themselves as a condition for their insurance.

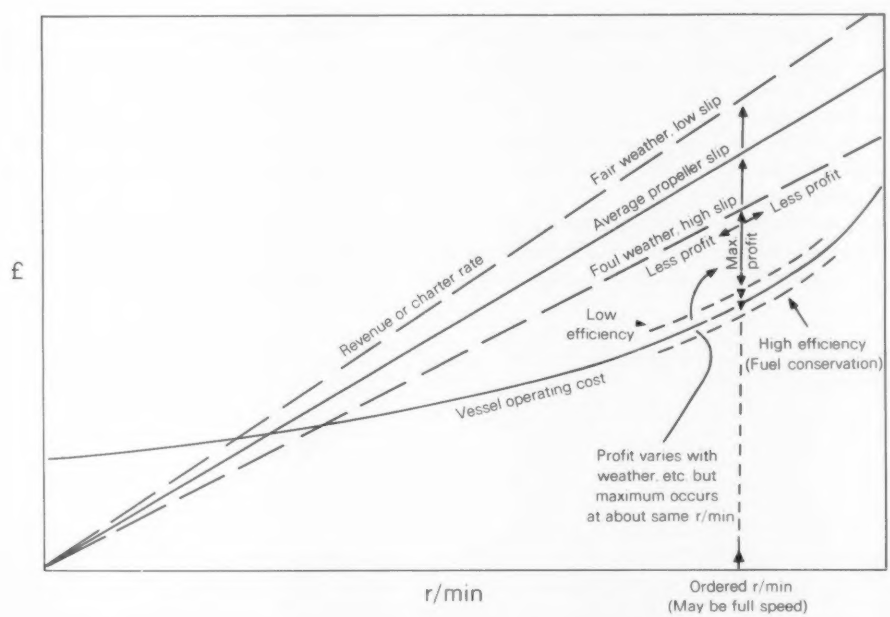


Figure 5. Schematic diagram showing effects of weather on vessel operating profits.

4. Financial aspects of the Ship Routeing Service

The Ship Routeing Service offers the shipping companies a dedicated professional service in which the close contact between the ship's Master and the shore-based centre allows the optimum routes to be selected. This expert selection of route can achieve appreciable savings in time on passage and a significant reduction in the damage to ships or cargo. Reductions in fuel consumption and in time off charter can also be obtained.

For example, the table below was obtained from one of the major UK shipping companies, which operated a very large fleet of UK flag and chartered vessels. This illustrates that substantial savings can be made in fuel usage and therefore in costs.

	Time saved (lost)	Equivalent fuel saving (loss)	
Pacific westbound	77.5 hours	£24758	Net, i.e. cost of routeing has been deducted from the full calculated bunker savings.
Pacific eastbound	(8) hours	£(2156)	
South Indian Ocean	36 hours	£5802	
Atlantic westbound	148 hours	£10053	
Atlantic eastbound	40 hours	£3060	

The value of ship routeing advice to the customer depends in the first place on the existence of adverse weather conditions and secondly on whether such conditions can be avoided. The potential economic benefits, such as the saving on fuel costs and heavy weather damage, can be realized only if conditions along the shortest route are adverse and there is a choice of a more favourable (and navigationally feasible) route.

In the 14 years since the Meteorological Office began the Ship Routeing Service, they have provided routeing advice to 3700 ships, tows, etc. and thereby earned a total of about £552000. The current fees for the Service are £150 for North Atlantic crossings and £225 for passages on other oceans. The Meteorological Office Ship Routeing Service, having the full back-up of forecast information for the entire northern hemisphere from the computer model, and access via the Global Telecommunication System to observations in both the northern and southern hemisphere is able to provide a full global ship routeing advisory service.

Annual receipts from the Service have been increasing steadily over the past three years owing to vigorous marketing and the recognized excellence of the product. They cover in full the staff costs of those directly involved in the Service, plus a significant contribution towards overheads.

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NOTICES

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